THE PHILLIPS LABORATORY'S REP-RATE PULSER FOR HIGH-POWER MICROWAVE SOURCE DEVELOPMENT

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Abstract

The Phillips Laboratory has recently received a rep-rate pulser that will be used as a driver for the high power microwave (HPM) sources under development at the lab. The pulser consists of a computer-controlled high-voltage DC power supply, intermediate capacitive store, pulse transformer, four 20 Ω pulse forming networks (PFN's) in parallel, and a self-breaking output switch. A Macintosh computer running LabVIEW (National Instruments) software controls the pulser and data acquisition system. As received, the pulser has a 5 Ω impedance and can deliver up to a 500 kV, 500 ns pulse to a matched load. The results of the testing of this configuration into a matched resistive load will be given. At the present time, a higher impedance pulser would better serve the Phillips Laboratory, so the pulser has been reconfigured to a single PFN giving a 20 Ω output impedance. The results of these test at rep-rates up to 40 Hz will also be given.

System Description

The Electromagnetic Sources division of the Phillips Laboratory is primarily interested in the development of high-power microwave (HPM) sources. The Phillips Lab rep-rate pulser will be used as a driver for these developmental sources, which generally appear to the pulser as a low impedance (≤20 Ω) e-beam load. Originally the pulser was designed to deliver up to 500 kV to a 5 Ω load at rep-rates of a few Hertz in a one second burst. A complete description of the pulser while it was undergoing final tests before delivery has been given previously[1,2], so only a summary will be included here for completeness. A block diagram of the pulser configured as it was received is shown in Fig. 1. The high-voltage DC power supply is SCR phase controlled, has 480 V, 3-phase input power, and a transformer/rectifier stack output rating of 42 kV at 127 kW. The power supply output voltage, charging time, rep-rate, and number of pulses are controlled by a Macintosh computer running LabVIEW software. The charge voltage, rep-rate, and number of pulses are parameters that are selected by the operator in the screen room and then the computer controls the operation of the experiment.

The power supply charges a 55 μF (ten 5.5 μF capacitors in parallel) filter bank, which upon command from the computer, resonantly charges the 10.4 μF (four 2.6 μF capacitors in parallel) intermediate storage bank. The inductor in the resonant circuit has a value of 222 mH and the switching is accomplished with three 25 kV ignitrons connected in series. A high-voltage diode stack is included in series with the ignitrons and charging inductor to hold the charge on the intermediate bank after charging and allow the ignitrons to quench. The 10.4 μF intermediate storage is configured as 2 capacitor banks in parallel, each with its own triggered, gas-purged spark-gap connecting the bank through low-inductance buswork to the primary of a 1:13.5 iron-core transformer. The parallel switching scheme serves to reduce the stray inductance in the primary of the PFN charging circuit. These switches are triggered with a commercially available 100 kV, dual output trigger generator that is triggered from the controlling computer. The PFN (56 nF equivalent capacitance) is resonantly charged from the intermediate storage through the transformer until the self-breaking output switch closes, thus delivering the PFN energy to the load.

The sequence of events that comprise a pulse cycle of the pulser will be summarized. The power supply initially slow charges (10's of seconds) the filter bank to approximately 2/3 of the desired voltage. After the slow charge the power supply fast charges (10's of ms) the filter bank to the final value. The intermediate storage is then resonantly charged through the ignitrons in approximately 4 ms to about 1.6 times the filter bank voltage. This charge cycle transfers slightly over half of the energy in the filter bank to the intermediate bank and causes the filter bank voltage to fall back to the value obtained at the end of the slow charge cycle. After a time delay (~5 ms) to ensure the ignitrons have quenched, the PFN is then resonantly charged through the transformer to approximately 13.5 times the intermediate store voltage at which time the output switch self-breaks delivering the energy to the load. In the case of rep-rate operation the sequence is repeated, starting at the fast charge of the filter bank, for the desired number of pulses.

The configuration of four 20 Ω PFN's in parallel to give the 5 Ω impedance and 500 ns pulse width provides for flexibility to change the impedance and pulse width parameters. For instance,

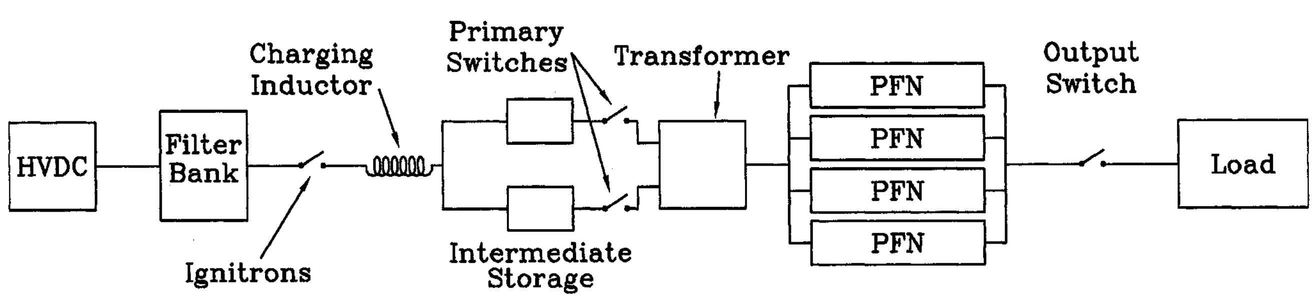

Figure 1. Pulser Block Diagram.

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14. ABSTRACT
The Phillips Laboratory has recently received a rep-rate pulser that will be used as a driver for the high power microwave (HPM) sources under development at the lab. The pulser consists of a computer-controlled high-voltage DC power supply, intermediate capacitive store, pulse transf01mer, four 20 .Q pulse forming networks (PFN's) in parallel, and a self-breaking output switch. A Macintosh computer running Lab VIEW (National Instruments) software controls the pulser and data acquisition system. As received, the pulser has a 5 .Q impedance and can deliver up to a 500 kV, 500 ns pulse to a matched load. The results of the testing of this configuration into a matched resistive load will be given. At the present time, a higher impedance pulser would better serve the Phillips Laboratory, so the pulser has been reconfigured to a single PFN giving a 20 .Q output impedance. The results of these test at rep-rates up to 40Hz will also be given.

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only one PFN can be used to give a 20 Ω impedance with a 500 ns pulse width. Table 1 lists the possible PFN configurations. It should be noted that changing the PFN configurations will also change the PFN charging time and voltage step-up ratio, so care should be exercised to ensure the PFN's do not get overcharged. To date the pulser has been tested in the 4 PFN, 5 Ω and the 1 PFN, 20 Ω configurations.

Table 1. Possible PFN Configurations.

Number of PFN's	Impedance (Ω)	Pulse Width (ns)	Maximum Energy/Pulse (kJ)
4	5	500	28
2	10	500	14
4	10	1000	28
1	20	500	7
2	20	1000	14
4	20	2000	28

Set-up and Modifications at the Phillips Laboratory

The pulser was received at the Phillips Laboratory in a partially disassembled state without the original computer or data acquisition/control hardware. When the pulser was initially operated it was found that the set points in the original controlling software program (VI) were no longer valid. This was attributed to the longer control lines running from the computer to the pulser. The set points at the pulser control panel are determined by the computer according to the desired operating parameters and the longer control lines and associated voltage drop required that these set points be adjusted. This corrected the problems initially encountered in single-shot operation. However, when rep-rate operation was attempted it was found that since the computer used at the lab was faster than the original computer, it was necessary to modify the timing loops in the controlling software for correct operation.

Another problem encountered during operation at higher filter bank charge voltages (≥45 kV) was an occasional electrical breakdown in the air-insulated power supply enclosure. When this occurred the filter bank would dump in excess of 55 kJ through the power supply case destroying many of the control circuit components. It is believed that this problem can be attributed to the fact that the original pulser design and testing took place at close to sea level and the operation at the Phillips Lab takes place at an elevation of over 6000 ft. Relocation and enclosure within insulated boxes of some components within the power supply case remedied this problem. The pulser has since been tested up to the full charge voltage of 50 KV without breakdown.

Initially the operation of the pulser required two people, one to run the computer for control and data acquisition in the screen room and the other to physically push the buttons at the power supply control panel located at the pulser. The power supply control panel has since been duplicated within the screen room so that one person can operate the experiment, although at this time an additional person is in the pulser area to monitor its operation. The remote operation was initiated primarily because of concerns about personnel safety during the testing of developmental HPM sources in the future. A closed circuit television system monitors the entire experimental area during testing.

4 PFN, 5 Ω Test Results

The first set of tests were done on the 4 PFN, 5 Ω configuration to verify previously reported results[1,2] and to determine maximum rep-rate/voltage combinations. The measurements taken each shot are the filter bank charge voltage, intermediate store charge current, transformer secondary current (PFN charge current), and PFN output voltage into a matched load. For all tests reported, the load is a resistor matched to the PFN impedance. The digitized data for a 35 kV, 8 Hz, 5 pulse shot are shown in Figs. 2-5. Due to the limitations of the diagnostic system, each output voltage/transformer secondary current pair is recorded on a separate oscilloscope. This is accomplished by "teeing" off the signal cables into each scope and then external triggering the first scope on the first pulse, the second scope on the second pulse, etc. The signal used to trigger all oscilloscopes is the sync-out of the primary switch trigger generator. The filter bank voltage is monitored with a voltage divider that was constructed in-house, the intermediate store charging current and transformer secondary current are monitored with commercially available current probes (Pearson coils), and a voltage divider that was supplied with the pulser is used to collect the output voltage.

The power supply filter bank voltage shown in Fig. 2 starts at 25 kV, the voltage charged to during the slow charge cycle, then ramps up to 35 kV in approximately 125 ms. At the end of the pulse string the filter bank is automatically dumped back to zero voltage. Figure 3 shows the intermediate bank charging current, also rep-rating at close to 8 Hz. Parameters in the controlling software allow for adjustment of the filter bank charging time, which is the method used to fine tune the rep-rate. Figures 4 and 5 show the transformer secondary current (PFN charge current) and pulser output voltage. The transformer secondary current consistently reaches the same magnitude but the time that the output switch closes varies as indicated by the change in waveshape at the end of the PFN charge cycle. This output switch jitter is also evident in the output voltage waveforms shown in Fig. 5 which vary in magnitude and temporal location. It is always the case that the first pulse has the highest magnitude followed by decreasing amplitudes which level out from about the fifth pulse on. The variation in output pulse amplitude can be as much as 30% which is undesirable for source development work. Work is underway to convert the self-breaking output switch to triggered operation in an attempt to stabilize the amplitude of the output voltage.

As mentioned previously, the energy stored in the intermediate bank is transferred to the PFN's through the transformer via two triggered, gas-purged switches in parallel. In

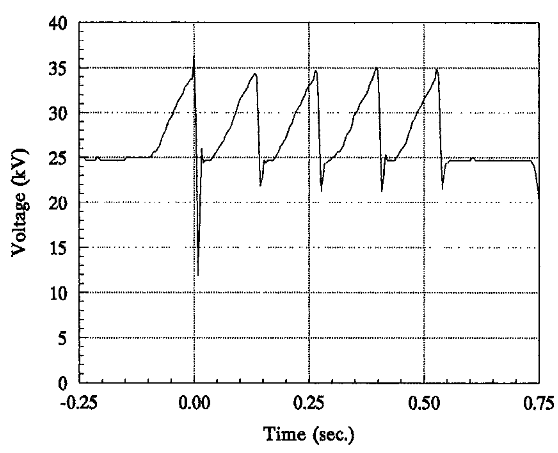

Figure 2. Power Supply Filter Bank Voltage.

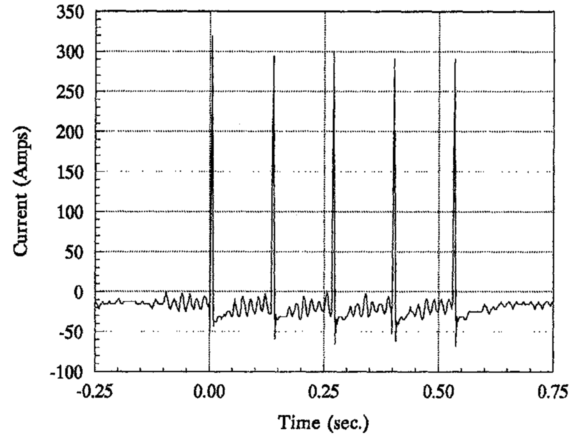

Figure 3. Intermediate Store Charging Current.

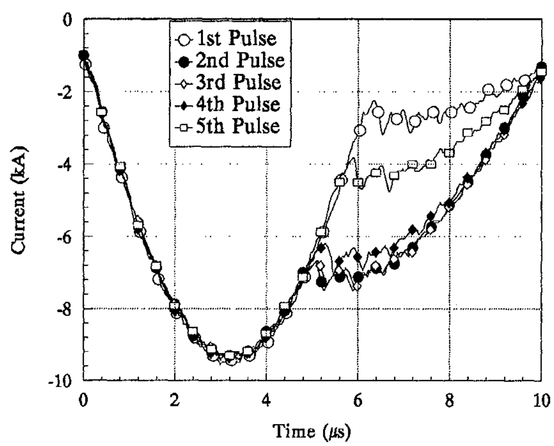

Figure 4. Transformer Secondary Current.

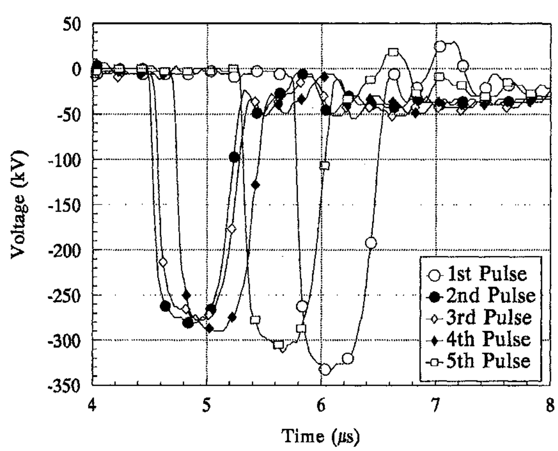

Figure 5. Pulser Output Voltage.

the event that only one switch fires, which has been observed, the energy stored in the half of the intermediate bank connected to the open switch is discharged through the charging lines to the transformer and then to the PFN. This discharge path is very inductive compared to the low-inductance bus work that is the normal discharge path and decreases the transformer secondary current by over 25%. A decrease in transformer secondary current is accompanied by a decrease in PFN charge voltage, which can cause the output switch to not fire on the first charge half-cycle. When this happens the energy rings between the PFN's and intermediate bank resulting in voltage reversal on the capacitors which is detrimental to their lifetime. Additionally, when the output switch does not fire at the end of the first half-cycle, it fires at some time later giving completely unpredictable output pulses. The amplitude of the pulse varies and in fact has been observed to be of opposite polarity, which could be catastrophic to certain microwave loads. During rep-rate operation, if the intermediate bank discharges through a single switch, that switch prefires on the subsequent pulse cycle before the ignitrons can quench resulting in the entire filter bank discharging through the ignitrons, primary switch, transformer and PFN. This is detrimental to all components involved so every effort to prevent the firing of only one primary switch must be made. A system is being designed that will detect low transformer secondary currents and prevent the next fast cycle from occurring. This coupled with the triggered output switch should minimize the potential damage to the microwave load as well as the pulser.

In light of the observations just made about the occasional firing of only one primary switch and the potential for damage to the pulser components, the operation of the pulser was modified to do the maximum rep-rate/voltage combination tests. The transformer and PFN's were bypassed and the output of the intermediate bank was connected directly to the 5 Ω load resistor. With this configuration the capabilities of the power supply, ignitrons, and primary switches could be tested to determine the limiting factor for rep-rate operation without stressing the transformer or the PFN's. The parameters of interest were the maximum rep-rate of the power supply at specified voltages, the rep-rate capability of the ignitrons and primary switches, and the repeatability of the intermediate discharge waveform across the 5 Ω load resistor. With the intermediate bank connected directly to the resistor, the output of the intermediate bank behaves as an RC discharge with an RC time constant of ≈50 μs (C=10.4 μF, R=5 Ω). Numerous test were conducted in this configuration showing a variation in intermediate store charge voltage of less than 10% and a waveshape almost identical to an ideal RC circuit. For filter bank voltages of 30 to 50 kV in 5 kV steps, which corresponds to approximately 300 to 500 kV in 50 kV steps PFN output voltage, the maximum system rep-rate was found. The results of these test are summarized in Table 2. It turns out that for the 4 PFN, 5 Ω set-up, the limitation on the rep-rate is the time necessary to recharge the filter bank during the fast-charge cycle, which is determined by the allowable primary current draw from the 480 V, 3 phase supply. To obtain the 2 Hz, 50 KV data it was necessary to install an autotransformer on the primary side of the power supply that steps up the input voltage from 480 V to 520 V. Without the autotransformer the power supply will charge to 50 kV, but it

Table 2. Results of the 4 PFN, 5 Ω Tests.

Filter Bank Voltage (kV)	Maximum Rep-rate (Hz)	Number of Pulses
30	10	10
35	10	10
40	10	10
45	8	5
50	2	5

requires over one second. It should be noted that at 40 kV, 10 Hz the power supply is required to supply over 220 kW of power, well above its 127 kW rating.

Single PFN, 20 Ω Tests Results

At this time a pulser to drive 20 Ω loads is of more practical use to the Phillips Laboratory, so the pulser was modified for 20 Ω operation. Because of the modular design of the pulser, the conversion consisted of simply using one PFN, a single intermediate storage capacitor, one primary switch and three of the 10 filter bank capacitors. By reducing all storage capacitances and the PFN equivalent capacitance by approximately a factor of 4 the gain in the resonant charging circuits stayed about the same as for the fully configured pulser and resonant frequency doubled. The initial test were done with the transformer and PFN's bypassed as just discussed, with one intermediate storage capacitor (2.6 μF) connected to a 20 Ω resistor through a single primary switch. Once again the purpose of the test was to determine the maximum rep-rate the pulser could operate at for different charge voltages.

The first limitation encountered was that the trigger generator used to trigger the primary switches would not operate much above 10 Hz. This unit is a commercially available device (Maxwell Laboratories model 40230) rated at 100 kV output, 5 Hz operation. By installing a larger power supply and, changing some of the internal capacitor and charging resistor values this unit was made to operate at 40 Hz for over a second. The next component to fail was the trigger generator for the ignitrons which stopped firing reliably at about 20 Hz. This was remedied by simply replacing the charging resistor and now also operates at over 40 Hz for 1 second. Once 25 Hz operation was attained it became apparent that the controlling software would have to be streamlined and all unnecessary time delays removed. A time delay that must be tailored to the particular charge voltage is the delay from when the ignitrons stop conducting to when the primary switches are triggered. The higher the charge voltage, the longer this time delay must be to prevent the ignitrons from restriking, hence, this is another rep-rate limitation besides the filter bank recharge time for rep-rates above 10 Hz.

Another series of tests similar to those done for the 4 PFN configuration were done with the exception that no data was taken at 50 kV because it just takes the power supply too long to charge the filter bank. These tests are summarized in Table 3 and the intermediate store charging current for a 30 kV, 40 Hz, 40 pulse shot is shown in Fig. 6. The current maxima show considerable variation which can be attributed to two factors. The charging time of the intermediate bank is less than 2.5 ms and to capture the 40 pulses at a 40 Hz rate requires the sampling rate of the digitizer to be set such that only a few points of each charge cycle are recorded, therefore it is very likely that the current maximum is often missed. This is verified by looking at the 3rd, 6th, 9th, 12th, and 15th discharges of the intermediate bank into the 20 Ω resistor and observing that the variation in amplitude of the pulses is less than 10%. The second factor affecting the filter bank charge voltage and intermediate store charge current comes about in the firing of the phase control SCR's of the power supply. At 40 Hz, only a couple of 60 Hz half cycles are used each time to fully recharge the filter bank, and variations between requested SCR firing time in relation to the 60 Hz phase angle result in slight variations of the final voltage of the filter bank for each pulse.

A single PFN and the transformer were reconnected in the circuit to verify that when using only one PFN the pulser would still operate correctly. The pulser behaved very similar to the 4 PFN, 5 Ω configuration it was just at higher impedance and a faster rep-rate. The output pulse amplitude was highest on the first pulse, decreased on successive pulses until about the fifth pulse, then remained fairly constant.

Table 3. One PFN, 20 Ω Test Results.

Filter Bank Voltage (kV)	Maximum Rep-rate (Hz)	Number of Pulses
30	40	40
35	40	40
40	30	30
45	20	20

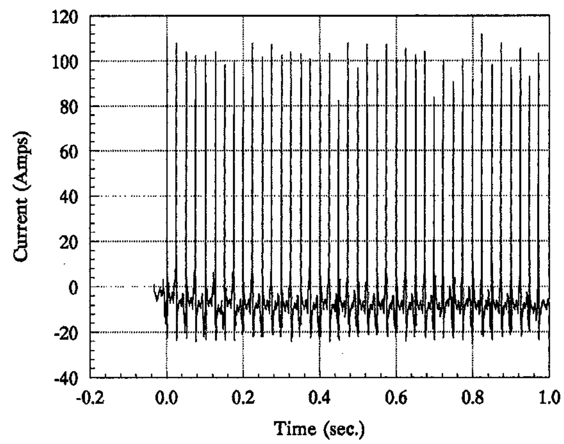

Figure 6. Intermediate Bank Charge Current for a 40 Hz Shot.

Conclusions

After an initial period of familiarization with the pulser and some slight modifications, the pulser was found to be very reliable and fairly easy to change in impedance and increase the rep-rate up to 40 Hz. It is necessary to implement a triggered output switch to provide for less variation in the amplitude from pulse to pulse, and circuitry will be added to detect low transformer secondary currents for the protection of the pulser and the microwave loads. The results of these modifications will be reported in the future.

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[1] A. Ramrus, et al., "Design and Performance of a One-Half MV Rep-Rate Pulser," in Digest of Technical Papers, Eighth IEEE International Pulsed Power Conference, 1991, pp. 982-5.

[2] A. Ramrus, et al., "A Compact One-Half MV Rep-Rate Pulser," in Conference Record of the 1992 Twentieth Power Modulator Symposium, 1992, pp. 68-71.